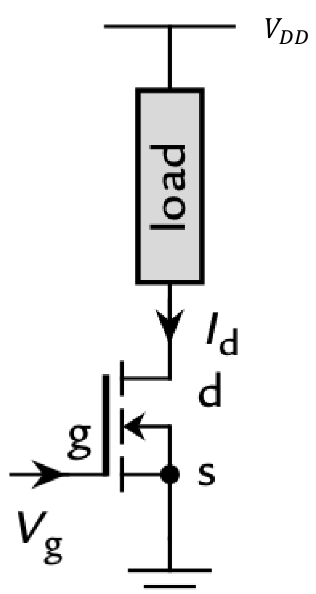
Selecting MOSFETs

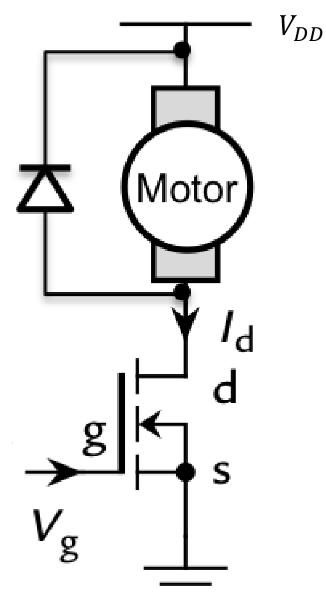
The MOSFET will be a crucial component to your design project. In general, there are two main subtypes of MOSFETs – those best suited for amplification (operation in saturation mode) and those best suited for power switching (operation in cut-off and triode modes).

In past guides for diodes, capacitors, etc. we have already covered the basics of how to search on manufacturer's and supplier's websites for specific parts, so this material will not be covered again. Rather, we will focus on how to interpret the new information from MOSFET datasheets which is relevant to this assignment.

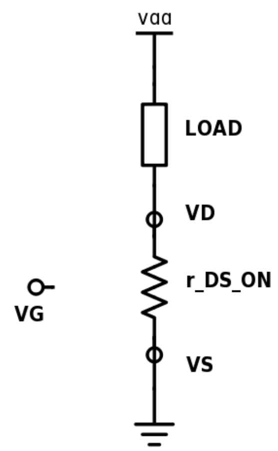
Consider the application: we are trying to switch a heavy load between two states, 'ON' and 'OFF'. In the OFF state, we do not apply a voltage across the load, and in the ON state we do. One might expect that this will roughly correspond to operation of the MOSFET in cut-off mode and triode mode respectively.

For the cut-off mode case, no current will flow through the MOSFET or load, and thus we have a relatively simple solution. However, the 'ON' case where the MOSFET operates in triode mode will depend on the circuit topology chosen. To make this a concrete example, let's assume we are trying to drive a relatively modest $2\ A$ load at $12\ V$, and we are investigating the IRF510 MOSFET (also used in Lab 4/5) for this application. Furthermore, we have decided on a common-source topology, meaning the load is connected as a drain load:





From the diagram above, we can see the load (represented as a motor in this case) connected as a drain load, meaning one terminal connects to V_{DD} and the other to the drain of the MOSFET. In this arrangement, if the MOSFET is in cut-off mode, we know that $I_D = I_{LOAD} = 0$, and thus we can achieve an 'OFF' state. To achieve an ON state, we would assume triode mode, which as we know from class is the most efficient state for use when switching a heavy load fully on. In this case, we replace the MOSFET with its equivalent model, a constant resistance $r_{DS_{ON}}$, as shown below.



At this point, we can solve the circuit. To do so, we now need to pull some information from the datasheet:

http://www.vishay.com/docs/91015/sihf510.pdf

Consider the first table, which lists $r_{DS_{ON}}$:

PRODUCT SUMMARY		
V_{DS} (V)	100	
$R_{DS(on)}$ (Ω)	V_{GS} = 10 V	0.54
Q_g max. (nC)	8.3	
Q_{gs} (nC)	2.3	
Q_{gd} (nC)	3.8	
Configuration	Single	

At some point in the document, you can typically find a value for $r_{DS_{ON}}$ directly listed, as above. With this value, we can estimate the power dissipated by the MOSFET:

$$V_S = 0\ V$$
$$V_D = V_S + r_{DS_{ON}} I_D = 0 + (0.54)(2) = 1.08\ V$$
$$P_{MOSFET} = (V_D - V_S) I_D = (1.08 - 0)(2) = 2.16\ W$$

One can note from the above that we have a design issue to resolve already. If $V_D = 1.08V$, then the motor supply would need to be selected to be $V_{DD} = 1.08 + 12 = 13.08\ V$ in order for the MOSFET to actually apply $12\ V$ across the load (and, by extension, for the load to actually draw the rated $2\ A$). Presumably, if we apply a lower voltage to the load it would not draw its full rated current.

To resolve this, you have two options. One is to select a MOSFET with a significantly lower $r_{DS_{ON}}$. This is a feasible solution, as many MOSFETs will have a value in the milli-ohm range. In this case, V_D will be small, and thus we can *approximate* that with $V_{DD} = 12\ V$, the load voltage will still be *close* to $12\ V$, even with the drop across the MOSFET considered. This has the added benefit of reducing the MOSFET's power loss (which we can see is high in the above calculation), and increasing the circuit's efficiency. The other option is to tolerate the voltage drop and increase V_{DD} to compensate. This is also feasible, but care must be taken if the load can draw a *varying* current at a *fixed* applied voltage (as is the case with most motors). If the load current may vary, then we could potentially apply more than $12\ V$ across the motor, damaging it. However, if the load current is fixed, this second option is also viable.

Assuming we continue with the above MOSFET (and that the load tolerates the reduced voltage applied in the 'ON' state while still drawing close to $2\ A$), we can estimate efficiency:

$$P_{LOAD} = (V_{DD} - V_D)I_D = (12 - 1.08)(2) = 21.84\ W$$
$$\eta = \frac{P_{LOAD}}{P_{TOTAL}} \times 100\% = \frac{21.84}{21.84 + 2.16} \times 100\% = 91\%$$

In this case, 91% of the power delivered by the supply is provided to the load, while 8% is lost as heat in the MOSFET. Assuming this meets our design requirements for this application, we can now continue to check the other maximum ratings of the MOSFET. Starting with power:

ABSOLUTE MAXIMUM RATINGS (T_C = 25 °C, unless otherwise noted)

PARAMETER			SYMBOL	LIMIT	UNIT
Drain-Source Voltage			V_{DS}	100	V
Gate-Source Voltage			V_{GS}	± 20	
Continuous Drain Current	V_{GS} at 10 V	T_C = 25 °C	I_D	5.6	A
		T_C = 100 °C		4.0	
Pulsed Drain Current [a]			I_{DM}	20	
Linear Derating Factor				0.29	W/°C
Single Pulse Avalanche Energy [b]			E_{AS}	75	mJ
Repetitive Avalanche Current [a]			I_{AR}	5.6	A
Repetitive Avalanche Energy [a]			E_{AR}	4.3	mJ
Maximum Power Dissipation	T_C = 25 °C		P_D	43	W
Peak Diode Recovery dV/dt [c]			dV/dt	5.5	V/ns
Operating Junction and Storage Temperature Range			T_J, T_{stg}	-55 to +175	°C
Soldering Recommendations (Peak temperature) [d]	for 10 s			300	
Mounting Torque	6-32 or M3 screw			10	lbf · in
				1.1	N · m

One can see that this device can tolerate a maximum power dissipation of $P_D \leq 43\ W$. This exceeds the power we expect to dissipate in this application, and thus we are within the provided rating. It should be noted that as the MOSFET dissipates power, it will heat up. The rating for P_D is typically given at *room temperature*, and must be **derated** (lowered) at higher temperatures – the factor for derating is given in this case by the 'Linear Derating Factor'. In many cases, a graph of allowable dissipation versus device temperature is also provided. To combat this, high-power designs such as thus one may add a heatsink to improve heat transfer away from the device. It should be noted that $r_{DS_{ON}}$ is often positively affected by device temperature as well, which may compound issues with power dissipation – real designs will need to carefully consider thermal management as part of the design.

We can also check that the drain current we are drawing is under the maximum limit. One can see from the above sheet that 'Continuous Drain Current' is given at $V_{GS} = 10\ V$, and is $5.6\ A$ at room temperature (derated to $4.0A$ at $100°C$ case temperature). In either case, we do not exceed this limit with a $2.0\ A$ load.

Lastly, we can check that we do not exceed the maximum allowable drain-source voltage for the chosen device. In the 'ON' state, where the MOSFET is in triode mode, V_{DS} is typically small – in this case, it was $1.08\ V$, which is significantly less than the allowable $100\ V$ limit above. The worst-case that we should examine will usually be when the MOSFET is in cut-off. In this mode, $I_D = 0\ A$, and thus no current flows through the load. This will usually mean that $V_D = V_{DD}$ (as we do not expect a voltage drop across a load with no current flow). In this case, $V_{DS} = V_{DD}$. If we chose $V_{DD} = 12\ V$, we would need a MOSFET with an allowable maximum V_{DS} of at least $12\ V$, a condition which the above MOSFET still meets ($100\ V$ limit). It should be noted that when the load is **inductive**, such as a motor or similar, it may generate a large spike in voltage when the load is turned OFF. This spike is applied **on top of** V_{DD}, meaning V_{DS} could temporarily spike much higher than expected. This can be mitigated by both (i) selecting the V_{DS} limit of the MOSFET to have a large safety margin and (ii) using a diode to limit the magnitude of the inductive spike (seen in the prior diagram).

Thus far, we can see that the MOSFET does not have any ratings exceeded in the above design. One last thing that we should note, however, is that a number of the values were given **only** at a specified V_{GS}. In particular, both $r_{DS_{ON}}$ and drain current were specified with $V_{GS} = 10V$. We can also see that V_{GS} should go no higher than 20V. Thus, we could not directly drive this circuit with a $0V - 3.3V$ input as per the design assignment. We would need a **second stage** that provides at least $10\ V$ at the MOSFET gate when we want the MOSFET to be 'ON' (triode), and less than V_T for the IRF510 when OFF (cut-off). Assuming we want everything to operate from a single supply (V_{SS}), we can see that a circuit which applies either V_{DD} or a low voltage (less than V_T) to the input would suffice. This second stage could be designed in a similar manner to the above, however the power and current would be very tiny – thus, a much smaller transistor could be chosen, and smaller transistors will typically have smaller V_T and thus be compatible with a $0V/3.3V$ input.